Adaptive Optics: The Atmosphere

Astronomy 525

Lecture 27

Outline

- Definitions
  - Active Optics
  - Adaptive Optics
- Wavefront distortions
- Characterizing the Atmosphere
  - Index of refraction changes
  - Structure function & structure constant
  - Coherence length
  - Critical time
  - Isoplanatic angle
- Why AO?

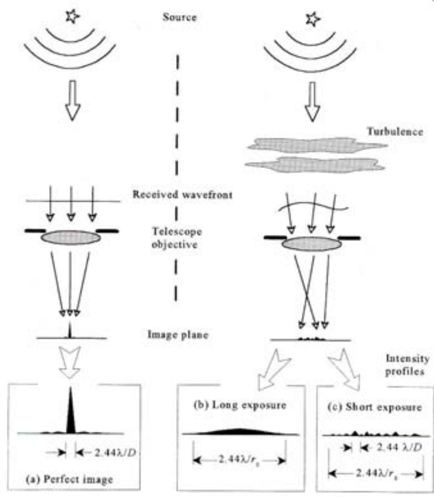
Adaptive vs. Active Optics

- Adaptive Optics:
  - Optical systems that measure and correct wavefront aberrations in real time
- Active Optics:
  - Slower type of system which adjusts the supports of the primary to compensate for flexure, etc.

Sources of Wavefront Errors

- Slot changing (t > 1 sec)
  - Change of focus
  - Optical decentering and misalignment
  - Segmented primary panel misalignment
  - Mirror figure errors
  - Internal turbulence
  - Local turbulence (dome seeing)
- Rapidly changing (t ~ 0.01 – 0.001 sec)
  - Atmospheric turbulence
  - (Wind loading?)

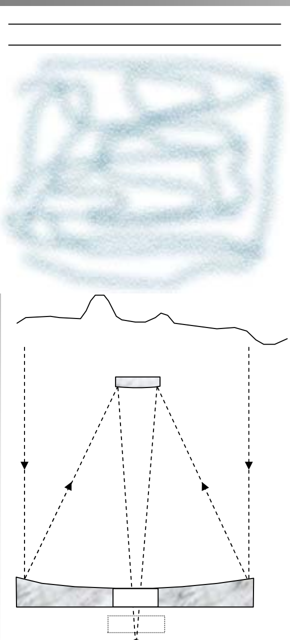
Stellar Images



Effects of turbulence on a stellar image

Hardy 1998 (fig 2.1)

Atmospheric Distortion (seeing)

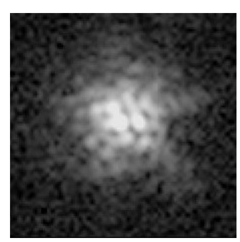


wavefronts from object

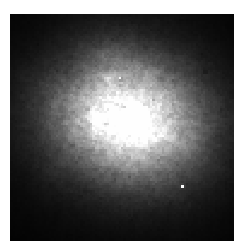
Atmosphere

distorted wavefront at telescope

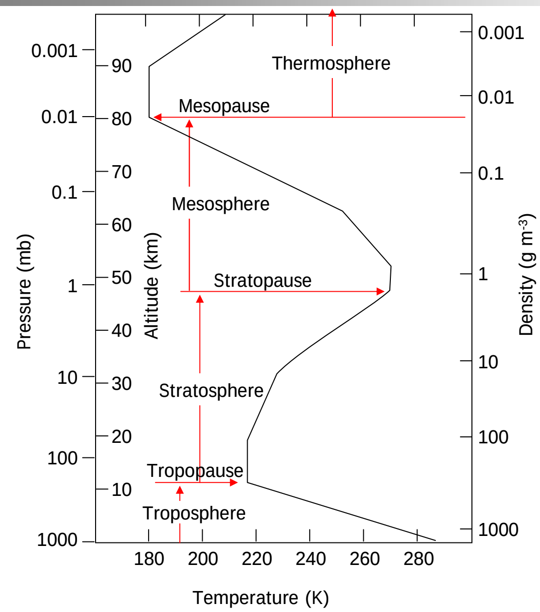
short exposure



long exposure

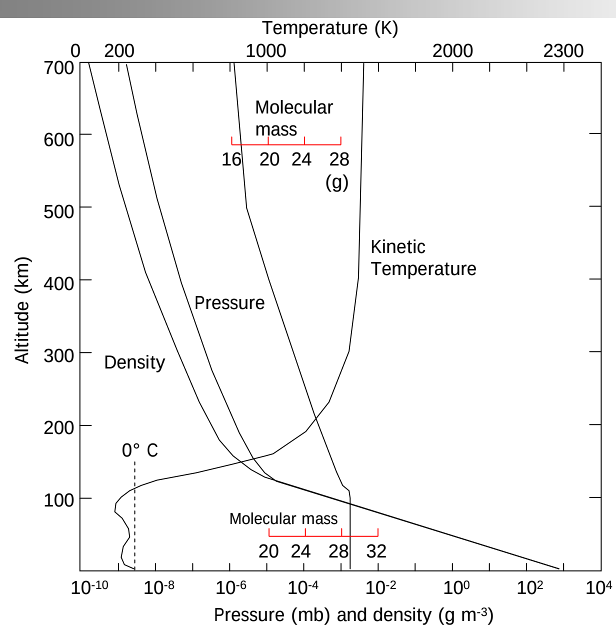


U.S. Standard Atmosphere



AO & The Amosphere 7 A525 - Lecture 27

P, T, ρ of U.S. Standard Atmosphere



AO & The Amosphere 8 A525 - Lecture 27

Atmospheric Turbulence

- To first order the refractive index of air is

  $$n = 1 + 7.9\times10^{-2}\,(P/T)$$

  where P is in atmospheres and T is in Kelvin.

- When small scale pressure and temperature fluctuations occur these cause changes in the index of refraction. However, pressure fluctuations equilibrate quickly whereas local temperature discontinuities are relatively stable.
- The temperature changes will cause a change in the optical path difference (OPD)

OPD changes

- The optical path difference (OPD) generated by a cell of length L will be

$$OPD(waves) = L\frac{\Delta n}{\lambda} = 7.9\times10^{-2}\frac{P}{\lambda T^2}L\Delta T$$

$$\approx 2L\Delta T \quad \text{(at STP in visible)}$$

- Thus for a ΔT ~ 0.1 K, strong wavefront perturbations are expected over a path of a few hundred meters.

Note: near marine surfaces or saturate soil, humidity changes can cause a maximum of 20% contribution to the structure function. (See IR/EO Handbook, Vol. II, Chapter 2.2)

Structure Function

- Structure function
  - Used to describe the expected variance in the refractive index between two points.

$$D_n \equiv \left\langle \left(n(\vec{r}_1) - n(\vec{r}_2) \right)^2 \right\rangle$$

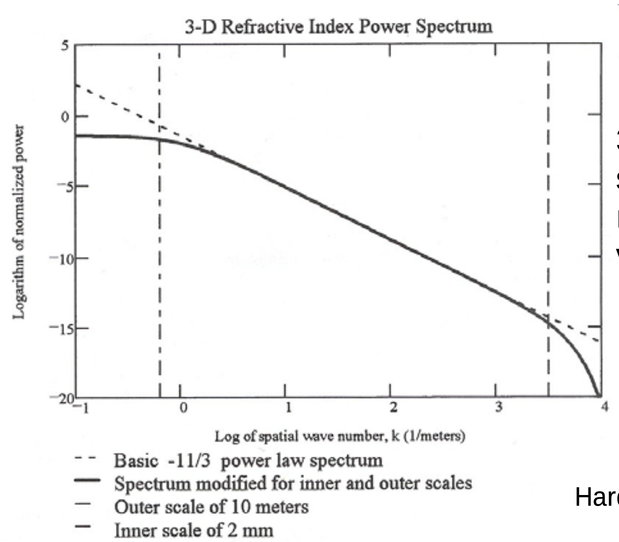
- It is found that atmospheric turbulence roughly follows a Kolmogorov spectrum

$$E(\kappa) \propto \kappa^{-5/3} \qquad (L_0^{-1} << \kappa << l_0^{-1})$$

[Kinetic energy of large scale motions is transferred to smaller and smaller scales, finally breaking up and energy is dissipated into heat by viscous friction.]

- With this spectrum $D_n(r) \equiv C_n^2(h) r^{2/3}$ — C_n^2 is called the structure constant

Power Spectrum of Index Variations



3D power spectrum of refractive index variations.

Hardy 1998 (fig 3.2)

Phase Structure Function

- The phase structure function
  - Characterizes the changes in the phase at the surface of a collection aperture – first derived by Fried
  - In MKS units

$$D_\phi(r) = \frac{115}{\lambda^2} r^{5/3} \sec(z) \int C_n^2(h) dh$$

where z is the zenith angle and the integral is performed over the beam path

Coherence Length

- The will be some length scale, r_0 , over which the gross wavefront distortion is limited to a uniform tilt.
- This distance is called the coherence length (or Fried parameter).
- Fried derived this as:

$$D_\phi(r) = 6.88 [r / r_o]^{5/3}$$

where

$$r_o = 0.185 \left\{ \frac{\lambda^2}{\sec(z) \int C_n^2(h) dh} \right\}^{3/5}$$

Seeing

- If we think of this a producing a diffraction-limited image, then the angular resolution limit due to "seeing" will be

$$\theta = \frac{1.2\lambda}{r_o} \propto \lambda^{-0.2}$$

So that the seeing gets better in the infrared compared to the visible

Coherence Time

- Another useful quantity is the coherence time, τ_o
- Coherence time
  - The time over which the near-field phase and far-field beam are relatively constant
  - In MKS units

$$\tau_o = 0.058 \left\{ \frac{\lambda^2}{\sec(z) \int C_n^2(h) v^{5/3}(h) dh} \right\}^{3/5}$$

- Where $v(h)$ is the vertical wind velocity profile.
- This expression is obtained by modeling the atmosphere as a set of phase sheets that are wind driven across the atmosphere.

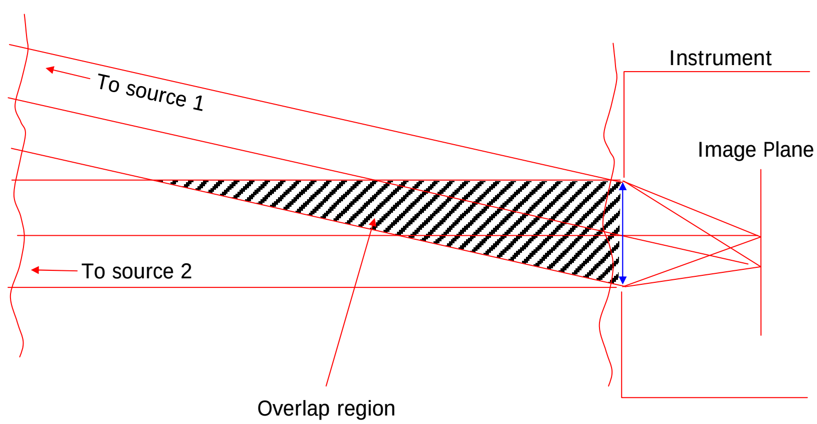
Isoplanatic Angle

- Isoplanatic angle, θ_o
  - Define the cone in which the optical path measured by a fixed point on the aperture will be constant
  - Again, in MKS units

$$\theta_o = 0.058\left\{\frac{\lambda^2}{[\sec(z)]^{8/3}\int C_n^2(h)h^{5/3}dh}\right\}^{3/5}$$

- This angle represents the maximum tolerable separation between a path sensed (by say a star) and the corrected path (the source).

Origin of Anisoplanism



Atmospheric Characterization

- r_o = Coherence (or Fried) length
  - Length over which the gross wavefront distortion is limited to a uniform tilt

$$r_o \propto \lambda^{6/5} \qquad \text{seeing} \quad \theta = \frac{1.2\lambda}{r_o} \propto \lambda^{-0.2}$$

- τ_o = Coherence time
  - Timescale over which atmospheric variations are frozen

$$\tau_o \propto \frac{r_o}{\bar{v}}$$

$\bar{v}$ = characteristic wind speed (~ 10 m/sec)

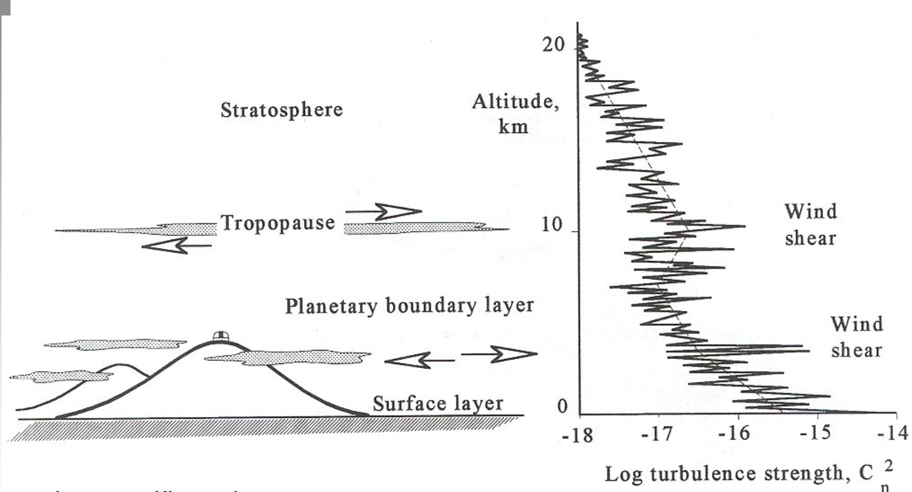
- θ_o = Isoplanatic angle
  - Maximum separation between source and guide star

$$\theta_o \propto \frac{r_o}{\bar{h}}$$

$\bar{h}$ = characteristic height (~ 6 km)

AO & The Amosphere 19 A525 - Lecture 27

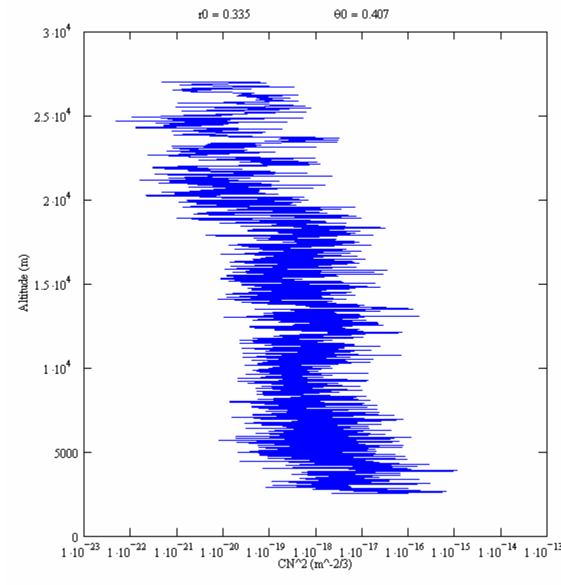
Atmospheric Layers



Hardy 1998 (fig 3.1)

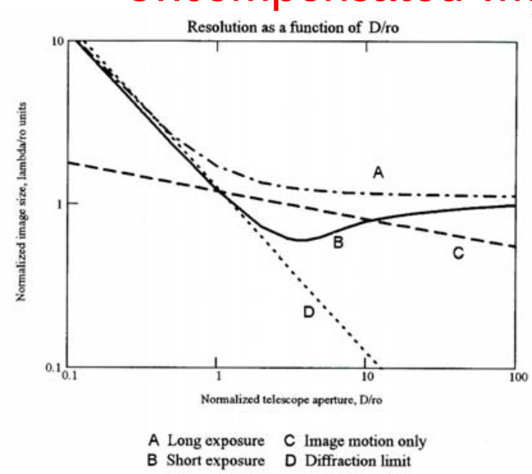
AO & The Amosphere 20 A525 - Lecture 27

C_n^2 – The Movie



Paranal: Mar-92 data

Uncompensated Image Size



Normalized image size for an uncompensated telescope

Hardy 1998 (fig 3.11)

Palomar "Seeing" Parameters

Band	Wave (um)	Nominal Diff. Limit. (")	Seeing (")	r_o (cm)	theta_o (")	tau_o (msec)	N_elem
V	0.50	0.0252	1.00	13	3	4	1185
R	0.75	0.0377	0.92	20	4	6	448
I	0.90	0.0453	0.89	25	5	8	289
J	1.25	0.0629	0.83	38	8	12	131
H	1.65	0.0830	0.79	53	11	17	67
K	2.20	0.1107	0.74	74	15	23	34
L	3.50	0.1762	0.68	130	27	41	11
M	4.80	0.2416	0.64	190	39	60	5
	6.00	0.3020	0.61	248	51	78	3
	8.00	0.4026	0.57	350	72	110	2
N	10.10	0.5083	0.55	464	96	146	1
Q	20.10	1.0116	0.48	1059	218	332	0
?	33.00	1.6608	0.43	1919	396	603	0

*Assumes 1.0" seeing at 0.5 μm

Why Adaptive Optics?

- The punch lines:
  - Improved image "quality" (smaller PSF)
  - Improved sensitivity (lower background)
- What are the potential gains?
  - Suppose seeing improves from 1" → 0.1"
- What is the sensitivity gain?
  - For BLIP (point sources), $f \propto \theta/D$

$$\Rightarrow f_{AO} = f_{PAL}\left(\theta_{AO}/\theta_{PAL}\right) = 0.1 f_{PAL}$$

Factor of 10 improvement!

- How big a telescope would you need to build to achieve this without improved seeing?

$$D_{big} = D_{PAL}\left(\theta_{PAL}/\theta_{AO}\right) = 50 \text{ meters}$$

How much would you pay for a 50m telescope?

Science Potential

- Resolving individual stars in galaxies
- Observation, classification, mass, and energy of distant galaxies
- Resolving stellar and protostellar system
  - Stellar disks, stellar companions (planets!?)
- High spatial resolution images of "surfaces" of planets, satellites, and asteroids
- Note: It is very expensive (and not practical?) to build big telescopes in space.

The Problem of Adaptive Optics

- Adaptive optics corrects wavefront distortions introduced by the atmosphere (and other sources)
  - What is it we need to do?
  - How hard is it?
  - How much does it cost?
  - What are the trade-offs?
- We need to characterize the atmosphere and see the scope of the problem
  - AO must sense and correct wavefront distortions real time!

Adaptive Optics System

- Correct distortions in the wavefront due to atmosphere in real time!
- Measure wavefront error (usually in optical) with a reference source
  - Natural and/or artificial (laser) stars
- Compute correction
- Apply correction to deformable optic (mirror)
- Science sensor (usually in the infrared) can integrate continuously
- Bandwidth needed depends on wavelength and seeing
  - 20 – 400 Hz (for infrared work)

Palomar Atmospheric Parameters*

λ (μm)	θ_{diff} (”)	Seeing (”)	r_o (cm)	τ_o (mS)	θ_o (”)	$N = (D/r_o)^2$
0.5	0.025	1.4	7	7	2	5100
1.25	0.062	1.2	22	22	7	520
1.65	0.082	1.1	31	31	10	360
2.2	0.11	1.0	44	44	15	130
10.0						

*Assumes 1.4” seeing at 0.5 μm